Developm ent of a low r oise l igh fran e rate CCD fo adaptive optics

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Abst a t

The Adaptive Optics CCD (ACCD) is a 32 by 64 frame transfer device offering low noise performance at high frame rates using skipper amplifier technology to achieve low noise performance. An array of 32 parallel readouts provides for fast framing at 1.5KHz with a design goal of 1.5 electrons (rms) noise. Potential applications for the ACCD are in wavefront sensing, tip/tilt sensing, and fast tracking. Eleven devices has been successfully packed and tested. An 8 electron rms noise floor has been measured using a single read from the skipper amplifier. Multiple reads are expected to diminish the noise to 2.5 electrons rms. Design goals are expected to be reached by changing the spacing between output amplifiers, using the newly tested low noise CUBIC amplifier, and through thinning and backside illumination.

1.( ) I rodr ctic

Atmospheric turbulence limits the spatial resolution of astronomical telescopes to the order of 1 arc second [1], and changes on a time scale from tens to hundreds of milliseconds depending on the wavelength of light used in the observation. The technology of adaptive optics has been developed to overcome atmospheric turbulence by providing corrections in real-time [2], and [3]. Detector sensitivity in the wavefront sensor, however, is one of the limiting factors in using adaptive optics for astronomical applications. Much of the interesting science is accomplished with objects of sufficiently high magnitude (greater than 10 in the visible and 14 in the near infrared [4]. Stellar magnitude limits for wavefront sensing using either a Shack-Hartmann or shearing interferometers type wavefront sensors using arrays of discrete photomultipliers or Charge Coupled Device (CCD) detector arrays are about magnitude 6 [4]. Recently Roddier has used arrays of Avalanche Photodiodes to perform curvature sensing of the incoming wavefront with magnitude 14 objects. [5]. Thus the successful fabrication and demonstration of a low noise high frame rate CCD would represent an important improvement in wavefront sensor performance, and it would increase the usefulness of adaptive optics systems to gather scientifically interesting data.

Reported here are the results of our effort to design, fabricate and test such a device. The required high speed is accomplished by placing an amplifier at the end of each column of pixels, instead of shifting the pixels through a horizontal shift register and reading them out with a single high speed amplifier. Read out noise in our CCD is minimized by using a skipper amplifier [6], [7], [8] which is capable of multiple nondestructive reading of the charge packet. This also allows the individual amplifiers to be relatively low speed (400 KHz), and whose readout electronics can be readily fabricated. These and other goals were incorporated into a design which was fabricated as a piggyback on one of JPL's Earth remote sensing flight projects (MISR--Multi-angle Imaging Spectral Radiometer). The first performance measurements of the device from a sample of 23 packaged chips are reported in Section 3.0. The results yield a device whose sensitivity is sufficient to be used in the Mt. Wilson 100 inch adaptive optics system. We have also identified necessary design and process changes needed to achieve our design goals which is described in the last section on improvements and future work.

2.0 Design and Fabrica ion

Our complete set of design goals are listed in Table 1. The CCD is design is a three phase frame transfer device in a 32 x 64 format. Initially, two designs of this device were fabricated, one with the floating gate amplifiers (i.e. the desired skipper amplifier) called ADAPT, and a design with floating diffusion amplifiers, named ADAPT2. The device with the floating diffusion output amplifier structure allowed us to initially experiment with the waveforms needed to drive the chip without the complexity of needing to accommodate the Skipper amplifier. These devices were placed on a mask set along with the MISR CCD, the wafer map is shown in Figure 1.

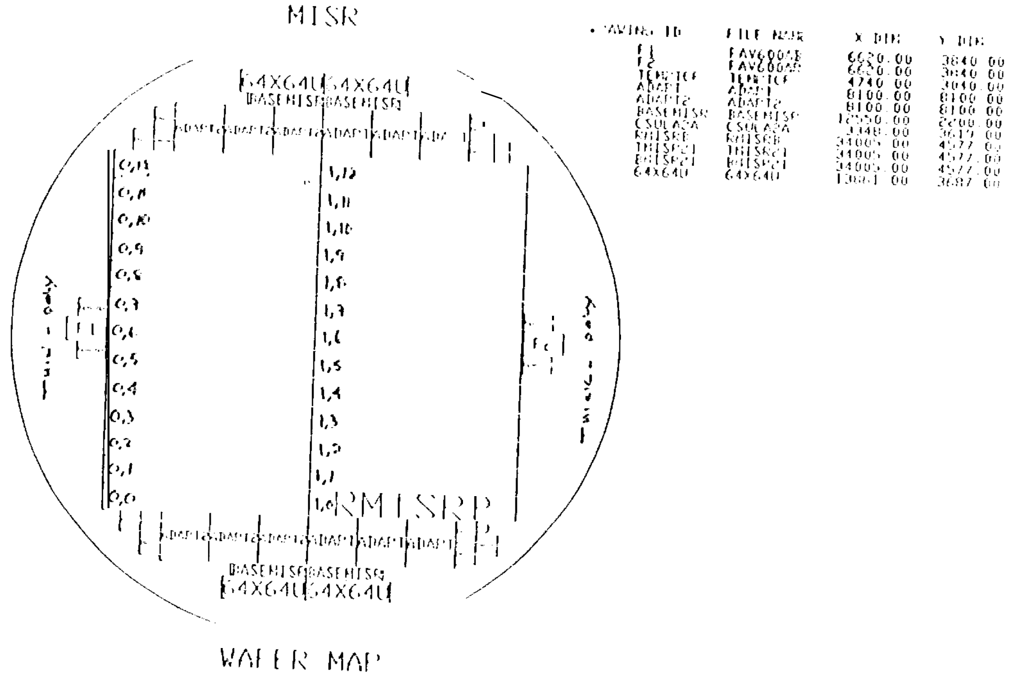
T ble 1: Design goals for a high frame ate, low noise CCD detector

A tribute	Quantity
For nat	32( ) x 64(V) rame transfer silicon CCD
Output ports	32 Skipper ati g gate amplifiers located at the end of each signal column
Pixel size	3 [illegible]
Read noise	1.5 electron rms noise floor
Frame rate	1,500 Hz
Quantum efficiency	60% min, 80% goal at 0.6 0.7 µm; 50% min, 70% goal at 0.8 n
Maximum signal	4,000 electrons min, 10,000 electrons goal
Frame transfer time	Transfer time/exposure time: 3% max, % goal. (900 ns/line max, ns/ line goal)
Dark current	1 electron/25ms per pixel at operating temperature (40 electrons/sec er pixel)
Operating temperature	Room temperature goal. Packaging and electronics should permit cooling if needed.

Table 1: Design goals for a high frame ra e low noise CCD detector

Attribute	Quantity
Clocking	Will allow column pixel binning and fast clocking out of columns without readout. Design will allow for unidirectional/bidirectional frame transfer
Jniformity	All pixels should meet design goals listed above.

igure : Wafer map of MISR CCD fabrication showing the skipper amplifier (ADAPT) and floating diffusion amplifier (ADAPT2) among the other test structures on the chords of the wafer.



The yield of the first lot from fabrication was so successful, that three ADAPT2 chips were blind packaged. An image of one of these is shown in Figures 2 and 3. Contrast the floatir g diffusion amplifier scheme in Figure 3 with the line drawing of the skipper amplifier given in Figure 4 to compare the added features. Subsequently a packaged ADAPT chip was produced from each a blind packaging sample and then a set of 6 chips were packaged after screening by probing.

3.(Res ı ts

A JPL logo was imaged by a 5x microscope objective onto the latest ADAPT CCD. The image after flat field correction is shown in Figure 5 showing all columns as functional and their level of output signal uniformity.

The first attributes we determined on the ADAPT2 devices were that there were no cosmetic defects in the columns. A uniform exposure was given to the full frame on the three blind packaged chips.

Figure 2: Photograph of ADAPT2 CCD in its 48 pi package. Inset ADAPT2CCD photomicrograph.

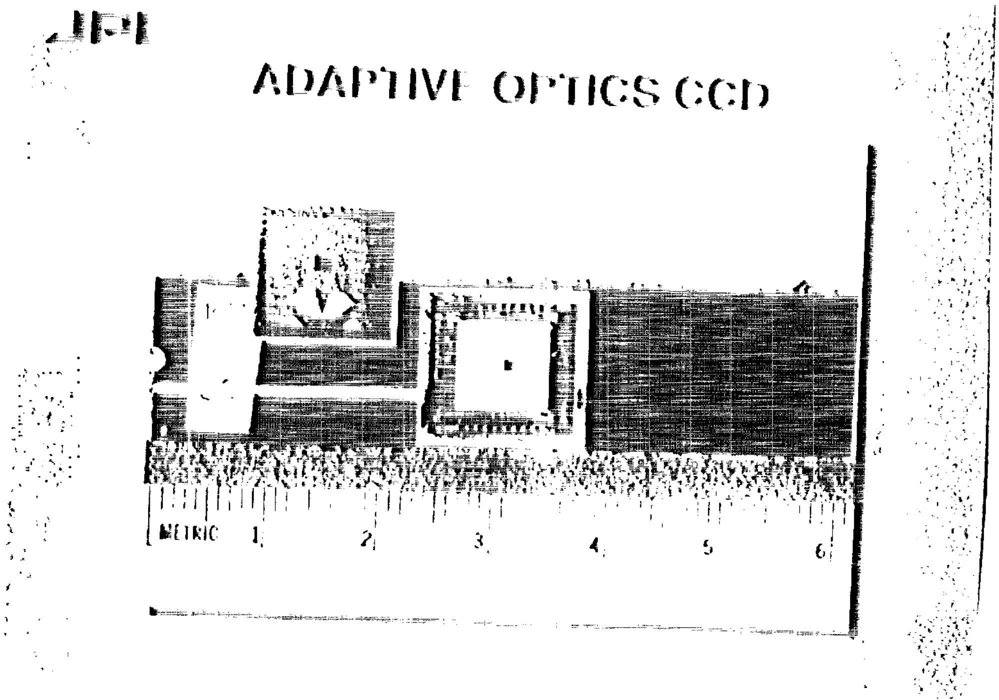


Figure 3: Photomicrograph of ADAPT2 CCD pixel structure. Inset is the floating diffusion amplifier structure.

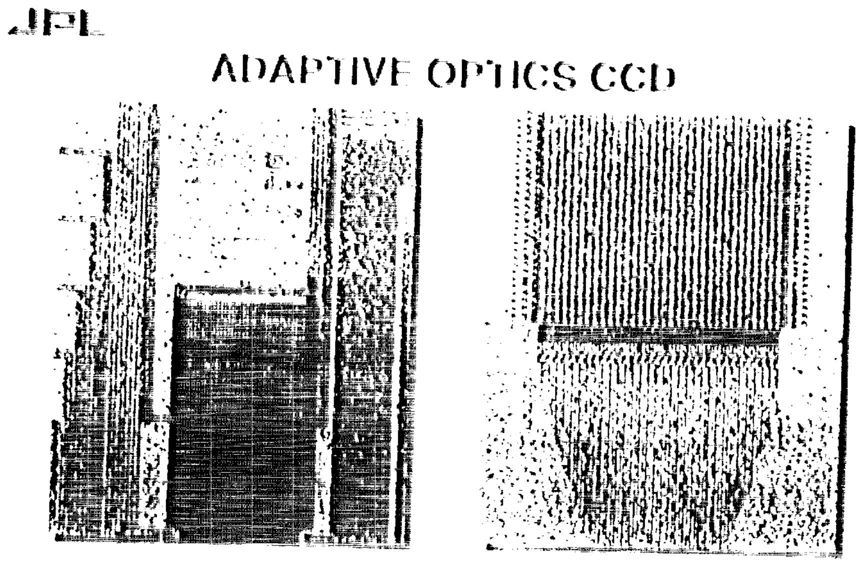


Figure 4: Line drawing of Skipper amplifier for the ADAPT2 CCD

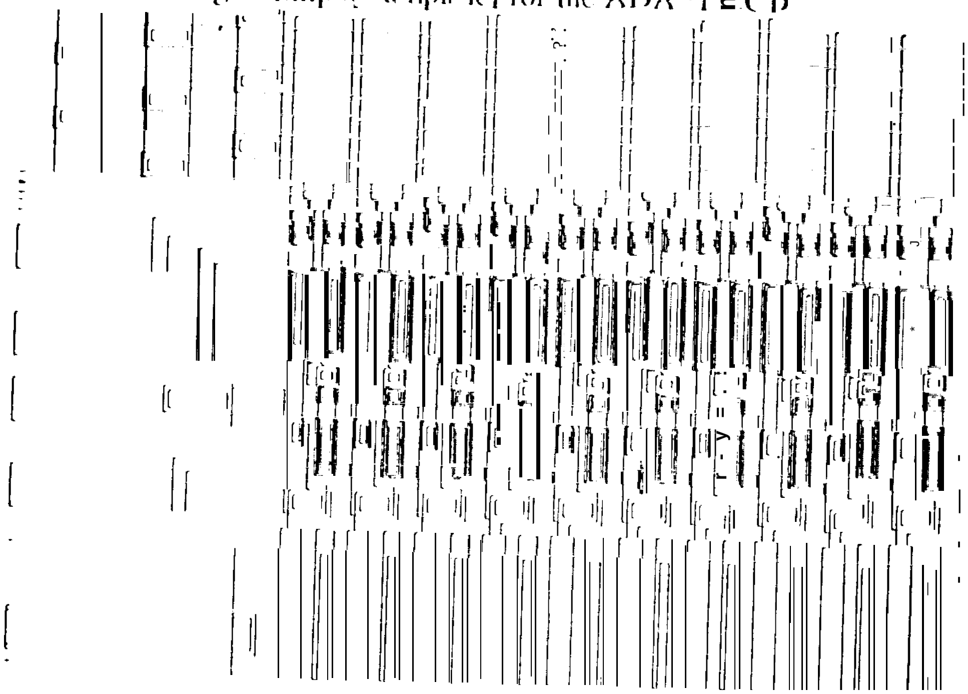
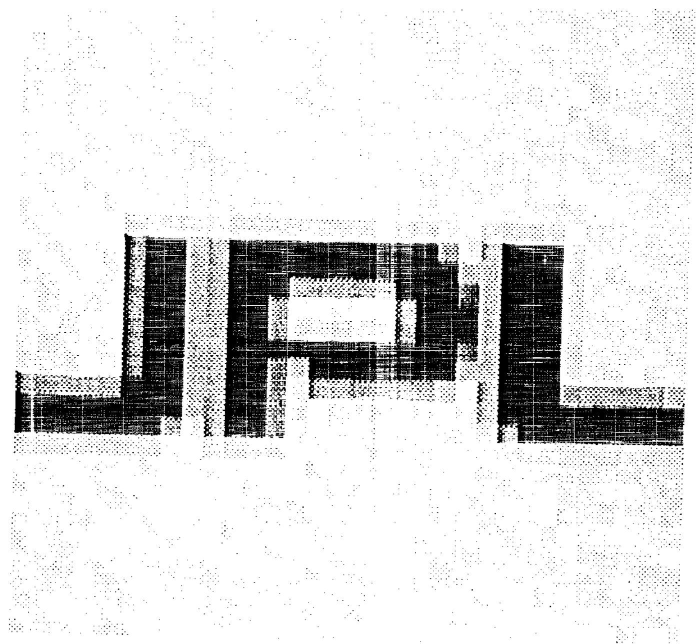


Figure 5: Flat field corrected image from a single read out of an ADAPT CCD



The amplifier gain, i.e. the ratio of output voltage for uniform input was such that there was only 20% difference between the highest and lowest outputs for all the amplifiers. The amount of gain nonuniformity within each amplifier was significantly smaller. The measured gain performance of all 96 amplifiers from the three packages ADAPT2 devices is shown in Figure 6. There is a bump at the end due to early errors in clocking which incorrectly read the last column, thus there is even more gain uniformity.

Later on we detected shorted amplifiers through gain measurements using the photon transfer technique, and enabled us to measure their performance for uniformity of response. All columns of the CCD were clocked as it maximum frame rate (1.5 KHz), although the sampling electronics at this time were not capable of this sampling rate, or capable of reading more than one output at a time. Photon transfer is a tool used to characterize the signal and noise properties of a CCD [9]. It can also measure the linearity of the CCD, its noise floor, and quantization gain (in signal units per generated electron). The photon transfer curve for an uncooled ADAPT is shown in part a of Figure 7. We can infer a quantization gain of 0.68 μV/electron, from which the noise floor is measured to be 19.4 electrons rms. The group of curves with the lower slope represents those amplifiers which are shorted to each other thus decreasing their noise by the square root of the number of contiguously shorted amplifiers.

An X-ray histogram is alternate method of determining quantization gain, the noise floor plus information of the charge transfer efficiency [9], [10], [11]. The CCD is exposed to an X-ray source which in our case is commercially available Iron 55 (Fe55). It emits X-ray photons at fixed energies, which for the K_α emission is 1620 electrons with an rms uncertainty of +/-12.7 electrons, the uncertainty due to the fano noise limit in the generation electrons in the CCD [12]. The corresponding emission for the K_β line is 1778 electrons +/-13.3 electrons. X-ray photons which fall entirely into a single pixel are measured over a large number of readout times. The histogram of all measurements should show a peak at these emission lines. Part b of Figure 7 shows the X-ray histogram for the same ADAPT2 device under similar operating conditions. the read out noise is computed by the variance in the absence of any signal.

Figure 6: The spread in gain for each of three ADAPT2 CCD chips.

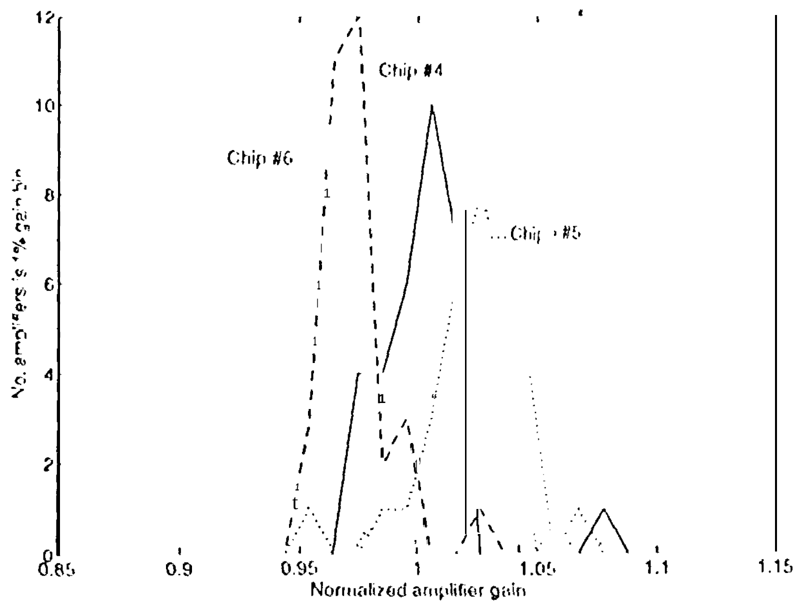
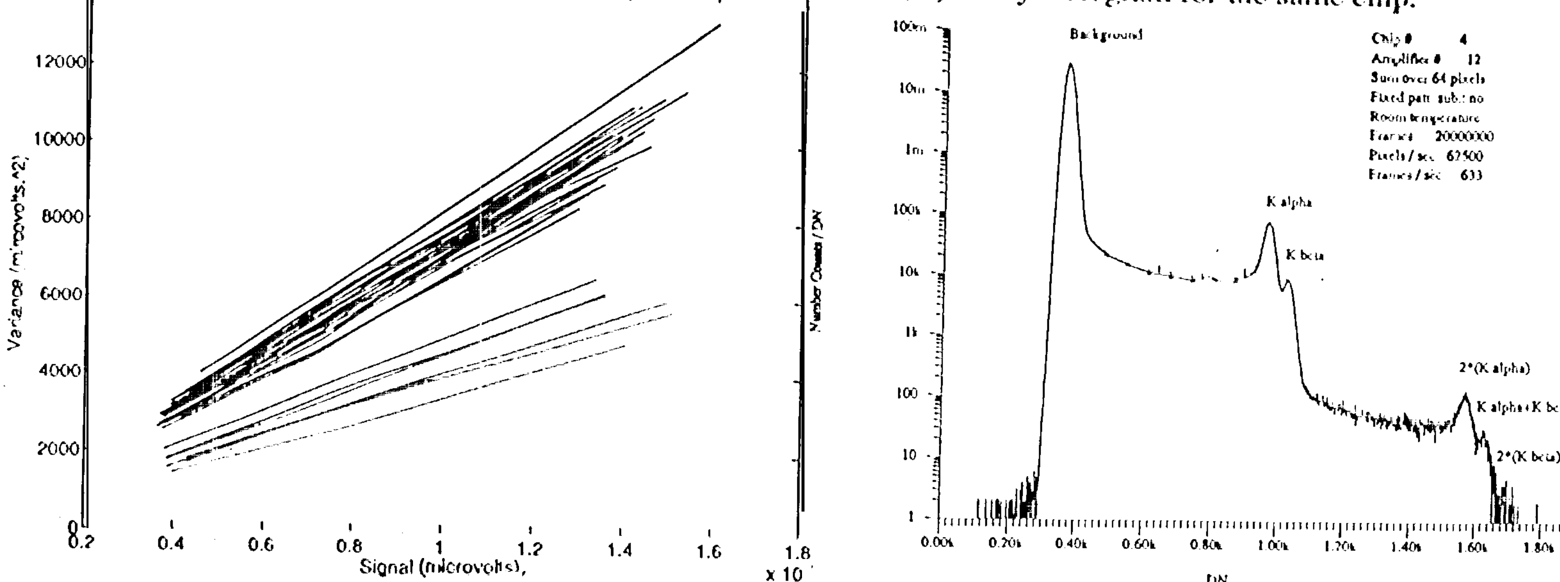
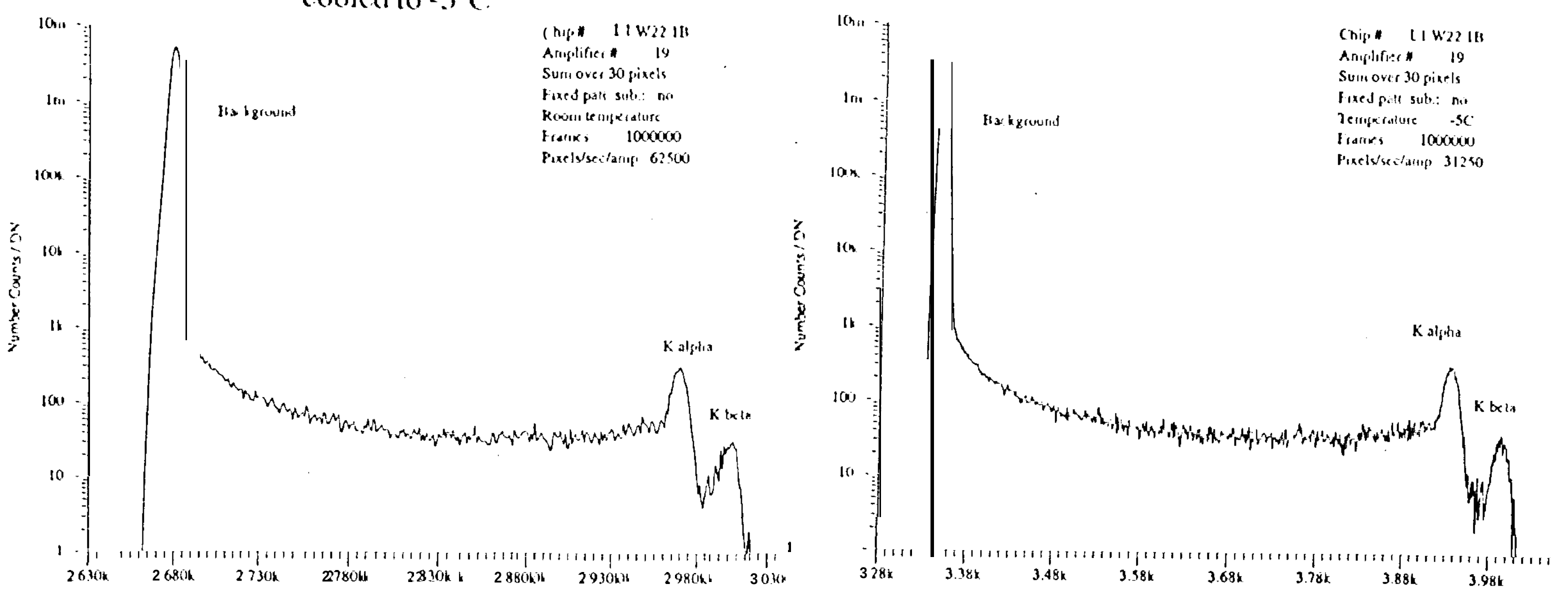


Figure 7: a) Photon transfer curve for ADAPT2 CCD, b) X-ray histogram for the same chip.



The corresponding X-ray histogram for an ADAPT CCD is shown in Figure 8. Part a) shows the response at room temperature, and part b) is the result when cooled to -5 C. The K_α and K_β emissions prominently stand out. Its read noise, however, was measured to between 8 and 9.2 electrons rms, 60-80% higher than expected from the design. We attribute this effect to diffusion Of electrons due to the close proximity Of the amplifier lines. The amplifiers are 10 μm apart which is the 1/e diffusion distance for this material. [13]. Thus after we complete our research into reducing the noise using the skipper amplifier, we expect our minimum to be 2.5 after 10 reads instead of 1.5. This effect will be eliminated in the improved design to be discussed in the next section.

Figure 8: X-ray histogram of an ADAPT CCD and readout in single read mode: a) uncooled; b) cooled to -5 C



In trying to determine the optimum voltage waveforms for driving the CCD for minimum read out noise, we observed an interesting effect due to the geometric arrangement of the read out amplifiers. In the process of determining the noise of isolated amplifiers by only unloading neighboring amplifiers we observed that the noise increased adjacent to the open amplifier. This effect is shown below in Figure 9. Note there is a commensurate decrease in the noise of shorted amplifiers. The bump in the noise figure for amplifier 16 is due to the presence of a bootstrap load resistor place there for other experimental reasons. We have also found that the ADAPT2 device can be damaged by leaving any of its amplifiers open relative to the others leaving a permanent increase in the. amount of amplifier noise.

4.0 Design improvements

In addition to eliminating the cross talk induced by the geometry of the amplifier lines, we also intend to use an improved lower noise read out amplifier and we also intend to maximize the quantum efficiency of the chip by thinning and back side. illumination. "1'0 increase the spacing between amplifiers we have considered, increasing the. pixel size of the CCD, and retaining the geometry of the amplifiers, and also we have considered alternating the placement of the amplifiers between the top and bottom of the chip. "Jim ability to clock both ways was written into the design goals and incorporated into our designs. A low noise amplifier was designed and built for the Cosmic Unresolved X-ray Background (CUBIC) camera, a 1024x1024 dc.vice with 4 readout amplifiers [10], [14]. Measurements on the CUBIC CCD have. demonstrated single read noise in a skipper amplifier of 2 electrons rms. An X-ray histogram using Fe55 is shown in Figure 10. The is amplifier has lower noise performance over ours due to optimizations made by using a lightly doped drain (LDD), a supernotch channel, and size optimization of the FET to lower its capacitance.

Figure 9: Amplifier uniformity for the cooled ADAPT chip in single read mode.

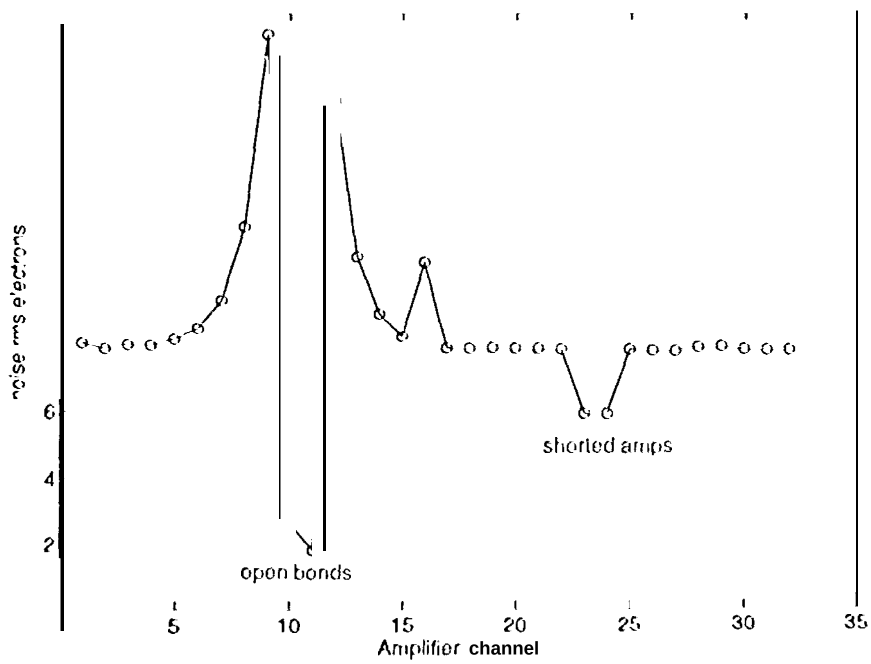
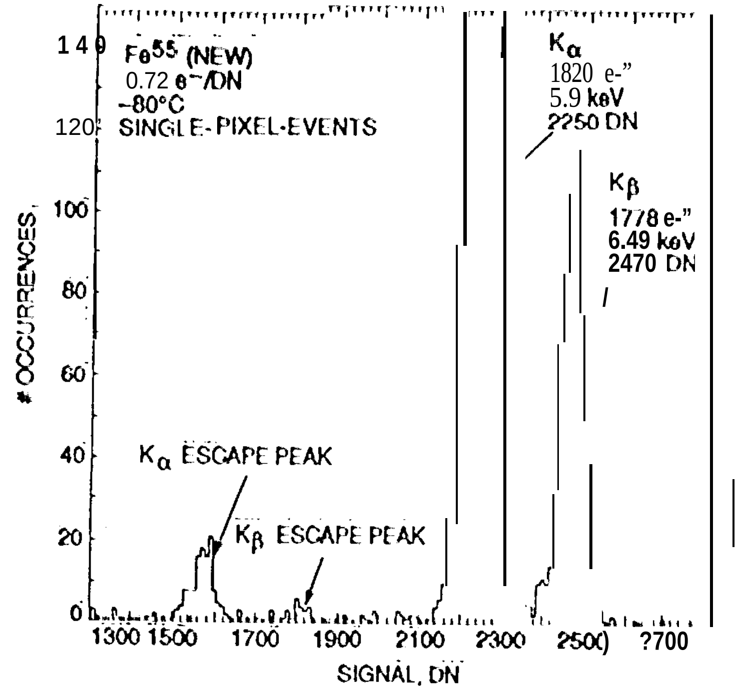
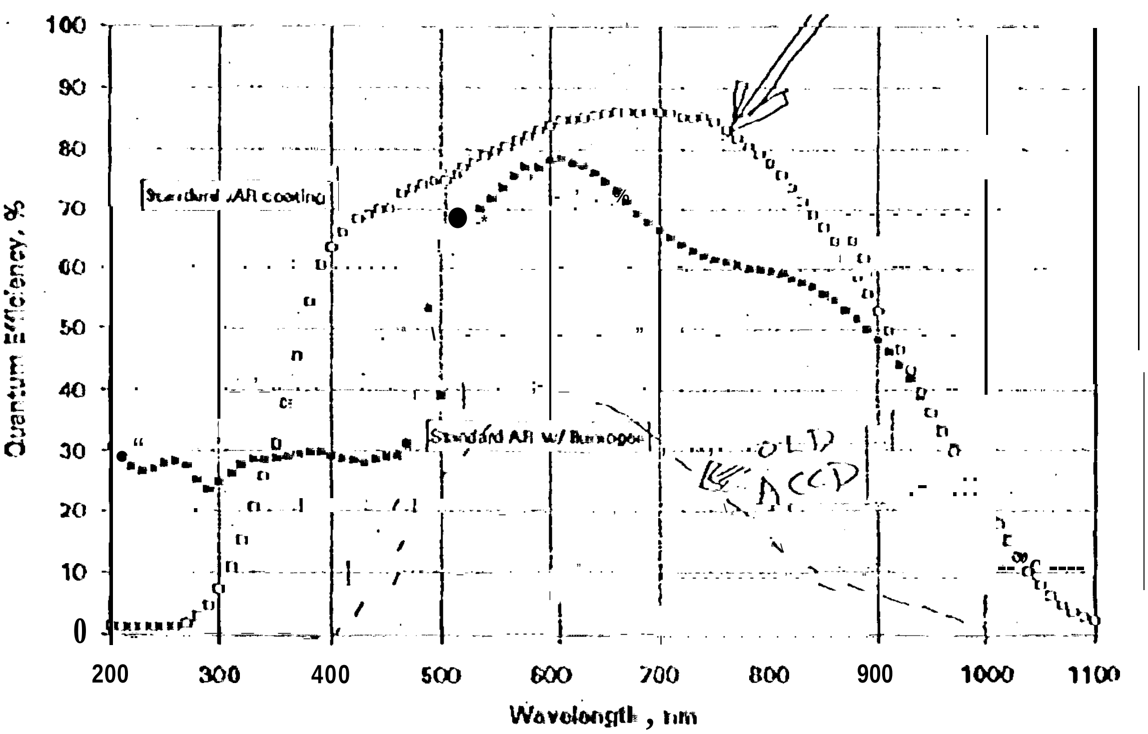


Figure 10: Fe55 histogram of a CUBIC CCD. Noise performance has been measured as 2 electrons rms.



Lastly, the quantum efficiency can be optimized through the process of thinning and backside illumination. Measurements of the current quantum efficiency fall below our design goals as shown in Figure 11. The top line snows the predicted increase through the combination of thinning and applying an antireflection coating to the back side of the CCD. This upper curve satisfies our design goals.

Figure 11: Predicted enhancement of the adaptive optics CCD using thinning, and backside illumination, and application of an antireflection coating.



5.0 Summary

We have designed and fabricated a high speed low noise detector 32 by 32 array for wavefront sensing and fast tracking. It uses 32 parallel low speed skipper amplifiers to achieve kilohertz frame rates. The best measurements made on the device using a single read on the skipper have demonstrated the performance at 8 electrons rms. And although higher than our design goal, its performance is sufficient to incorporate this chip into a Shack-Hartmann wavefront sensor for the coming adaptive optics system for the 100 inch Hooker telescope atop Mt. Wilson. Dark current is eliminated by cooling the device to -5 C, and the quantum efficiency is less than our goals due to the front side illumination architecture. We expect to reach our ultimate performance goals through improving the design by increasing the distance between amplifier by alternating them on the top and bottom of the chip, by using the lower noise CUBIC skipper amplifiers, and through backside illumination by thinning the device and applying an antireflection coating to the backside.

We intend to continue our investigations into reducing noise on the present cic.vice by multiple readout of the. skipper amplifier. Efforts are aiso currently underway to design and fabricate a set of driving electronics for the skipper CC]).

Acknowledgments

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6.0 References

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